

Recent liner experiments confirm plans for Magnetized Target Fusion

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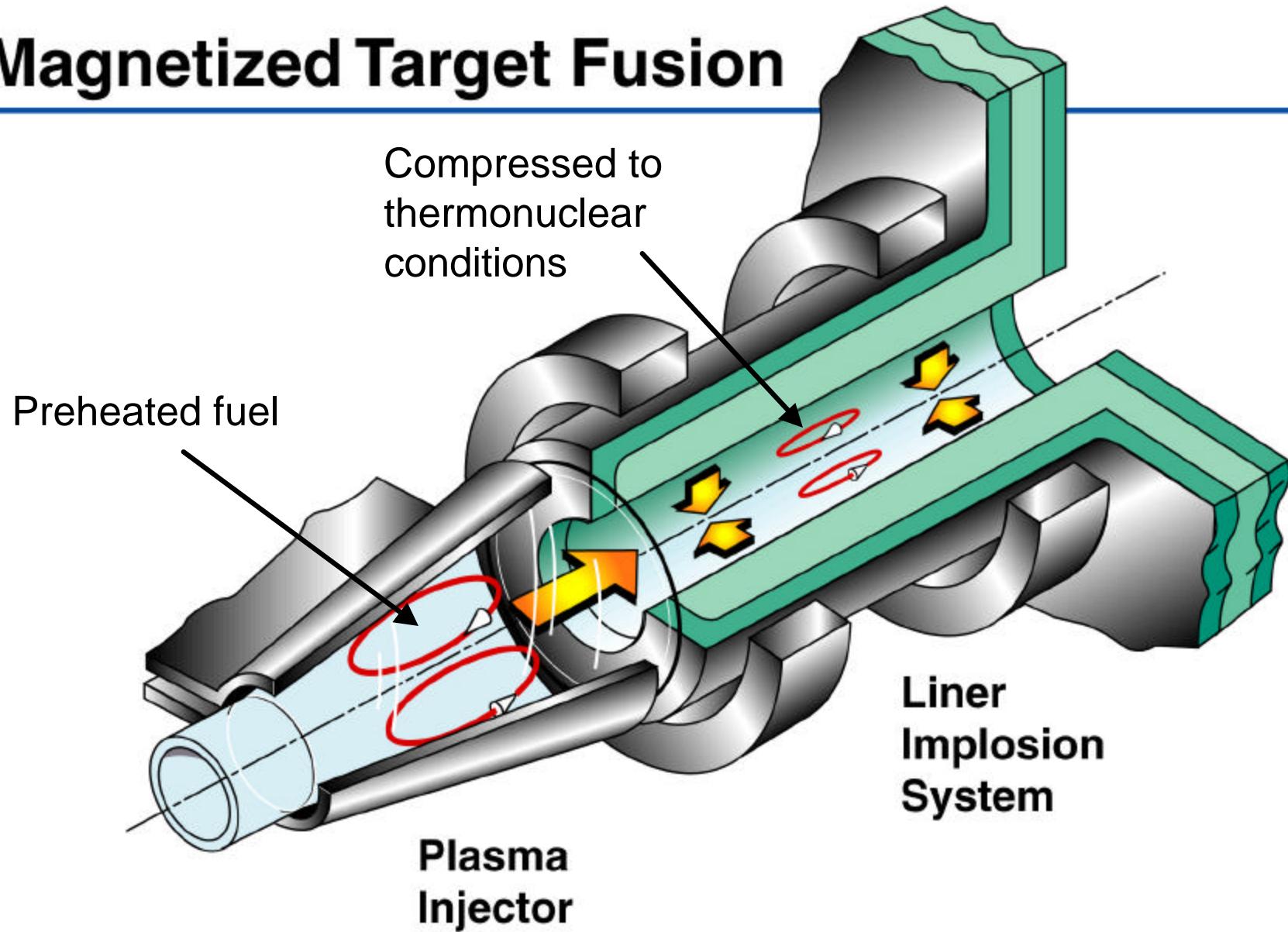
abstract

The premise of Magnetized Target Fusion is that fusion gain can be produced inexpensively using “liner” compression of a magnetized plasma. For adiabatic compression of a Field-Reversed Configuration (FRC), 10:1 radial compression gives impressive heating: 10 keV from an initial temperature of 250 eV. Recent experiments at the Air Force Research Laboratory will be described that have demonstrated how a 10-cm-diameter 1-mm-thick aluminum cylinder can be imploded using shock-free electromagnetic forces. The dimensions and energy density (liner velocity of 4 mm per microsecond) are the same as needed for interesting FRC compression. Although 10:1 radial compression implies considerable elastic-plastic deformation and thickening of the liner, experiments indicate highly symmetric deformation, and the inner surface of the metal remains a smooth cylinder according to an array of impact probes and side-on radiography. The time history of the radial implosion inferred by measuring the compression of a small magnetic field agrees with computer models of the implosion. Some further development of the liner implosion technique is necessary before liner-on-plasma experiments begin, but for the immediate future emphasis in MTF research has shifted to preparation of a suitable plasma target. Using models based on previous FRC experiments, LANL and AFRL are designing an experiment at Los Alamos that can generate a 5T pulse of magnetic field in 2.5 microseconds, giving FRC density $\sim 10^{17}\text{cm}^{-3}$ and T $\sim 250\text{ eV}$. The FRC dimensions (separatrix radius $\sim 2.5\text{ cm}$ and length $\sim 30\text{ cm}$) allow the FRC after formation to be translated and trapped in a liner close to the same size as that used for the liner implosion experiments. Diagnostics for FRC experiments will include a magnetic probe array to measure separatrix radius vs. axial position, side-on interferometry for density (and temperature by pressure balance), optical imaging for global stability, Thomson scattering for Te (and density independently), and spectroscopy for impurity content.

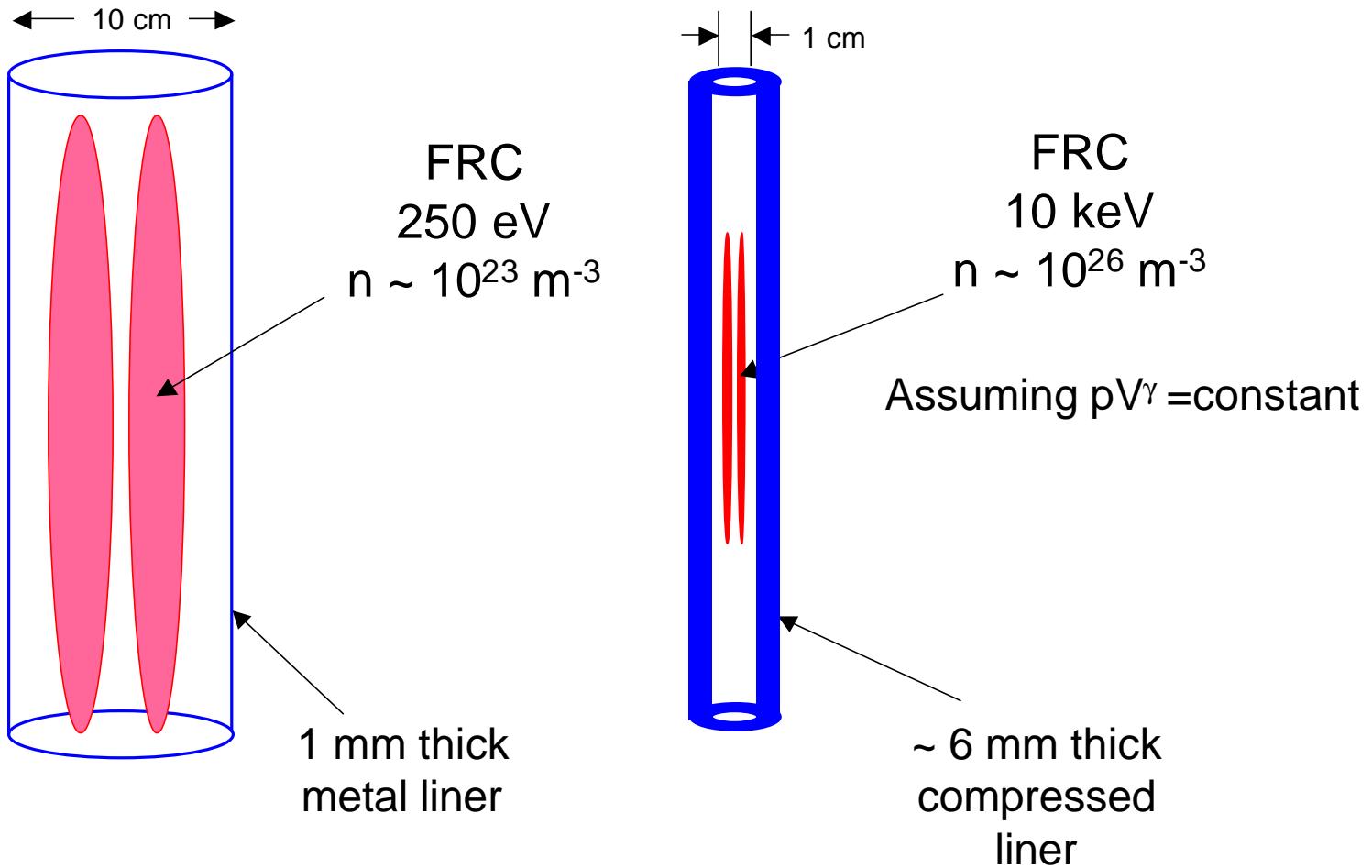
Main points

- For Magnetized Target Fusion (MTF) background info see: fusionenergy.lanl.gov or Snowmass CD
- The MTF configuration selected for first exploration is a Field Reversed Configuration (FRC) inside a cylindrical imploding metal shell (or “liner”)
- Los Alamos and AFRL used Shiva Star facility in 1999 to test the implosion of an FRC-compatible liner (no plasma and weak magnetic field for diagnostics purpose)
- The liner imploded as expected. Inner surface velocity was more than 4 km/second. Symmetry was excellent with radial convergence of more than 13:1.
- An experiment is being designed to study FRC target-plasma formation in the dense plasma regime ($n \sim 10^{17} \text{ cm}^{-3}$) suitable for MTF

Magnetized Target Fusion

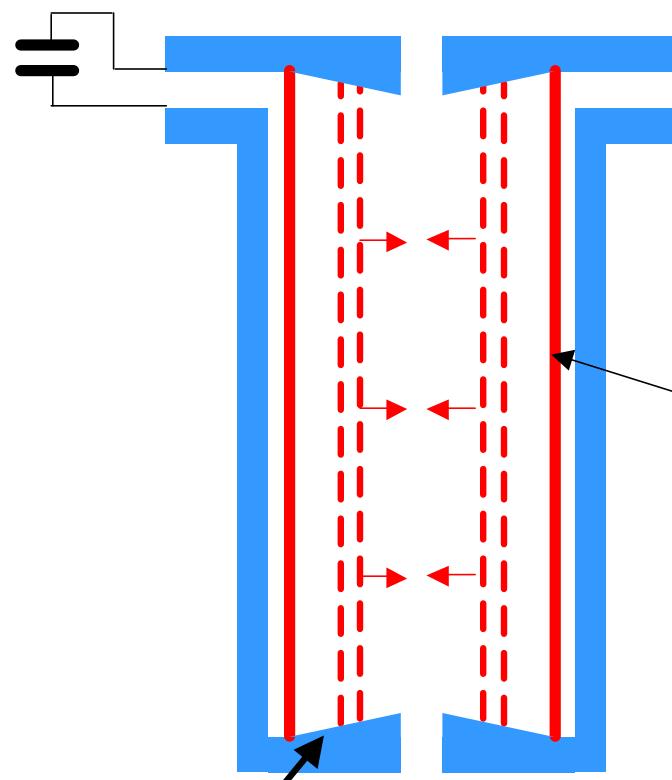


Adiabatic compression is effective



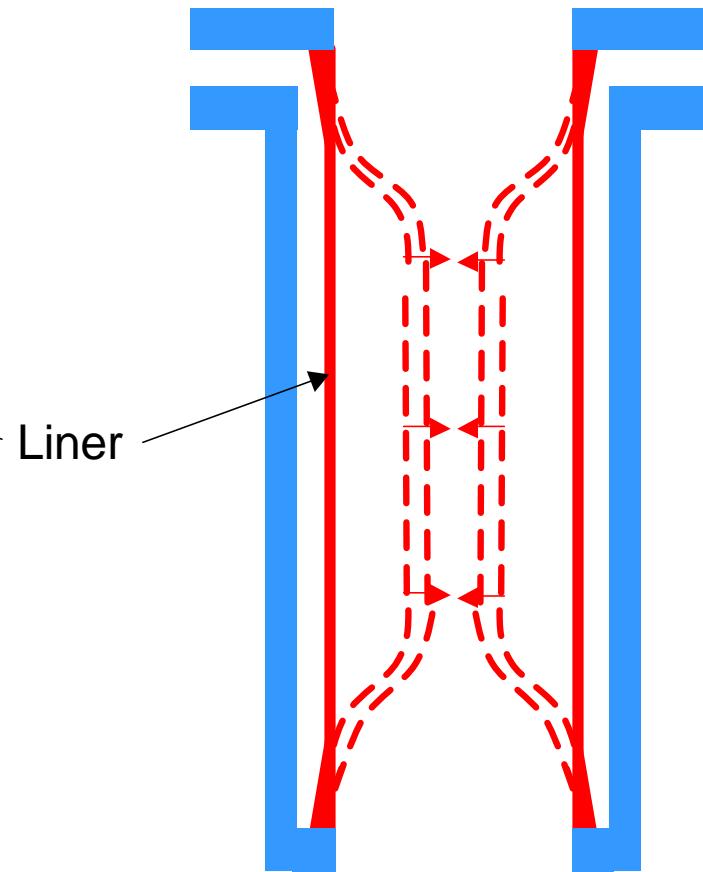
Connecting current to the liner

Uniform-thickness liner



Glide-plane electrodes
used in 1999 Shiva-Star experiments
would interfere with FRC injection

Variable-thickness or “shaped” liner

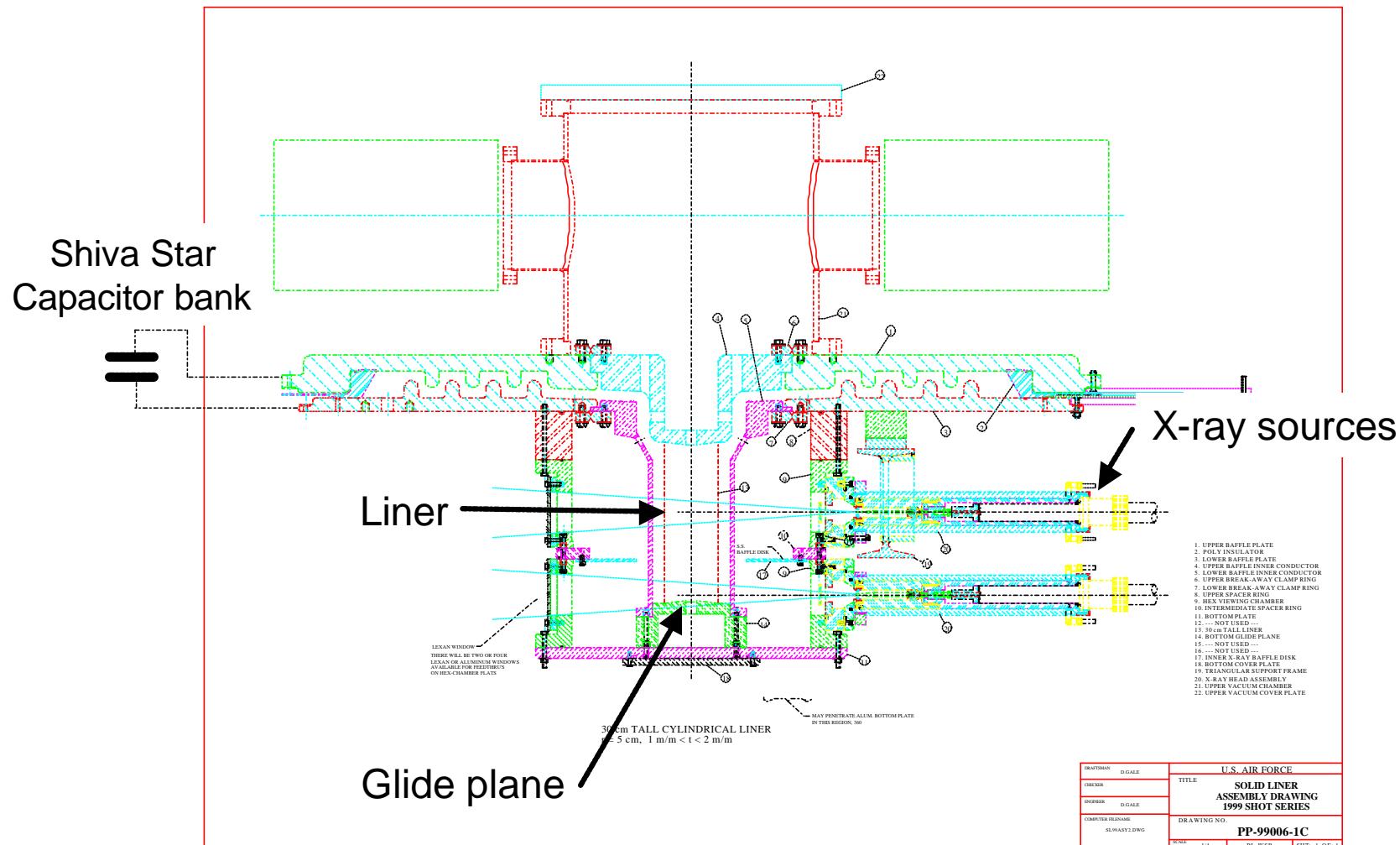


Shaped liner to be tested in the future

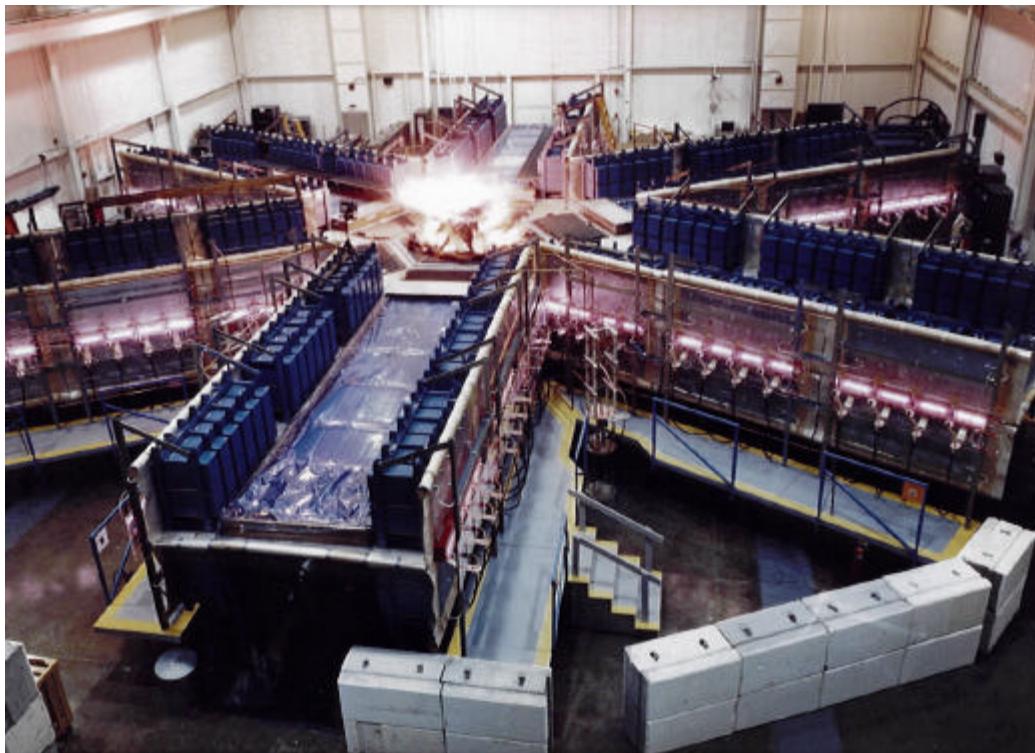
Los Alamos

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AFRL Assembly Drawing of Liner



Shiva Star Facility at AFRL



- 80 kV; 1300 μ F; 44 nH
- About 11 Megamp in 10 microseconds implodes 30-cm-long, 10-cm-diameter, 1.1-mm thick liner
- 5 MJ energy storage gives 1.5 MJ in liner KE

Purpose of Shiva-Star liner experiment

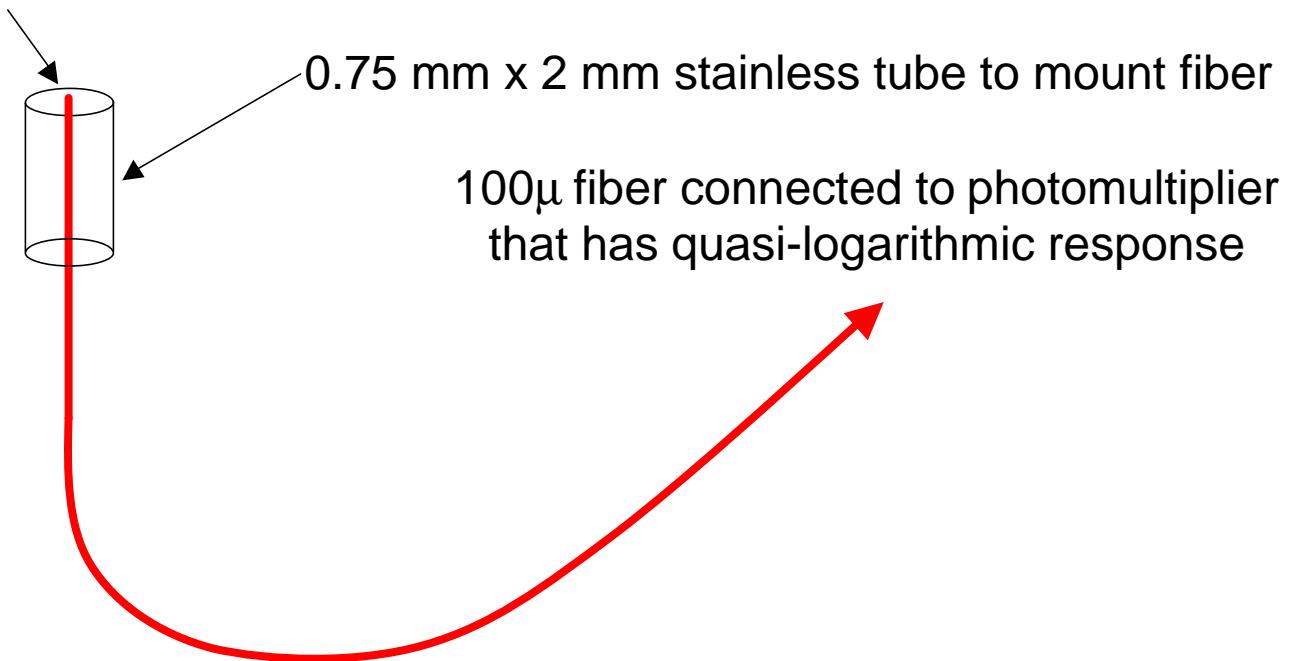
- Implode a “long” cylindrical liner (Length/Diameter = 3)
- Investigate gross liner stability at 10:1 radial compression;
(No instability expected given precision of liner fabrication,
but possibilities include helical kinks; destructive Rayleigh
Taylor, ...)
- Experiment does NOT address eddy-current heating by
internal magnetic field or plasma effects

Diagnostics

- Fiber optic impact probes to establish that inner surface of liner is properly located at end of 10:1 compression ($R \sim 0.5$ cm)
- Radiographs to characterize global symmetry
- Seed magnetic field and measure $B(t)$ to compare predicted trajectory $R(t)$ with experimental trajectory

Fiber optic probes

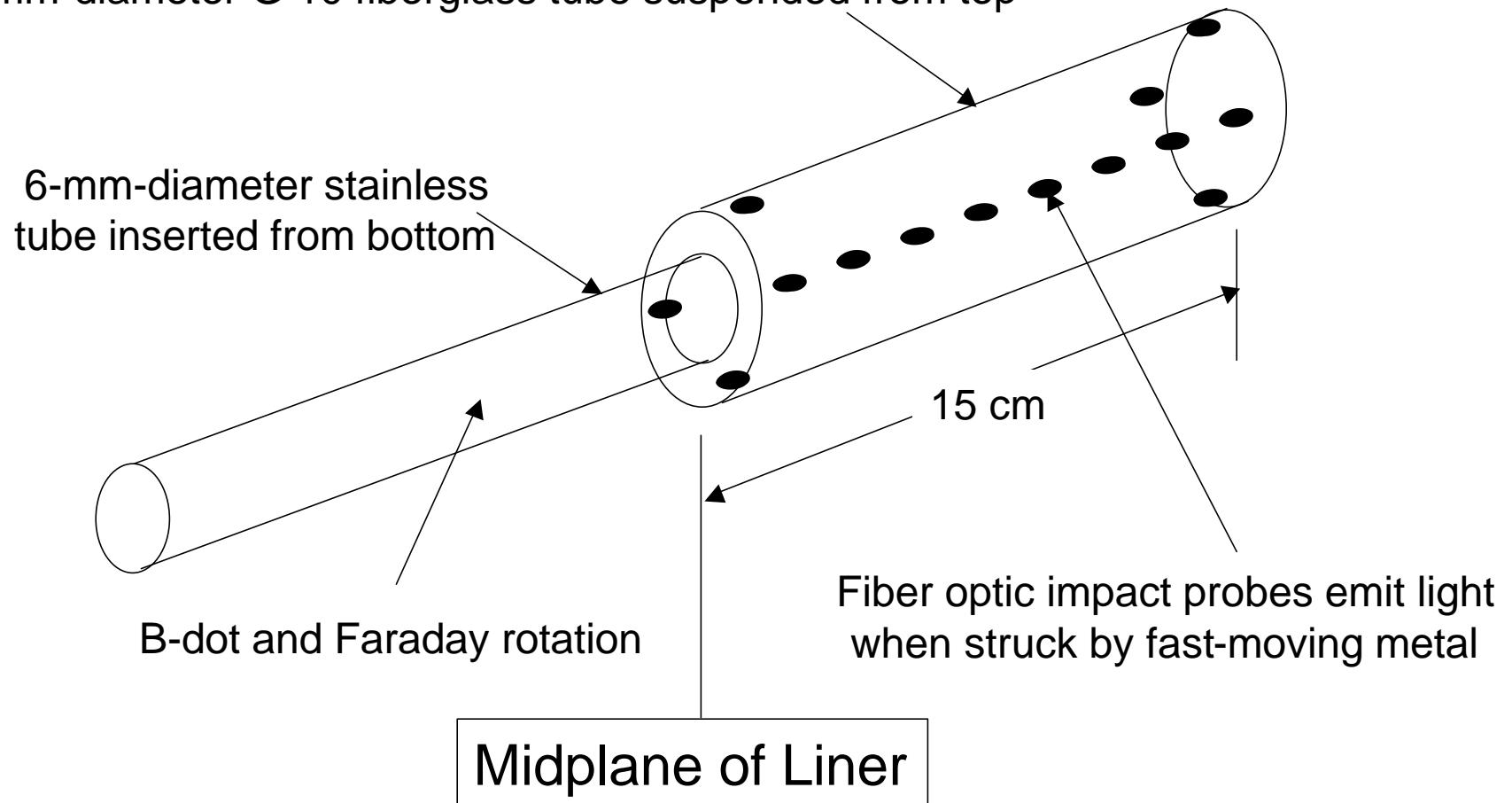
Polished ends covered with opaque 25μ aluminum foil



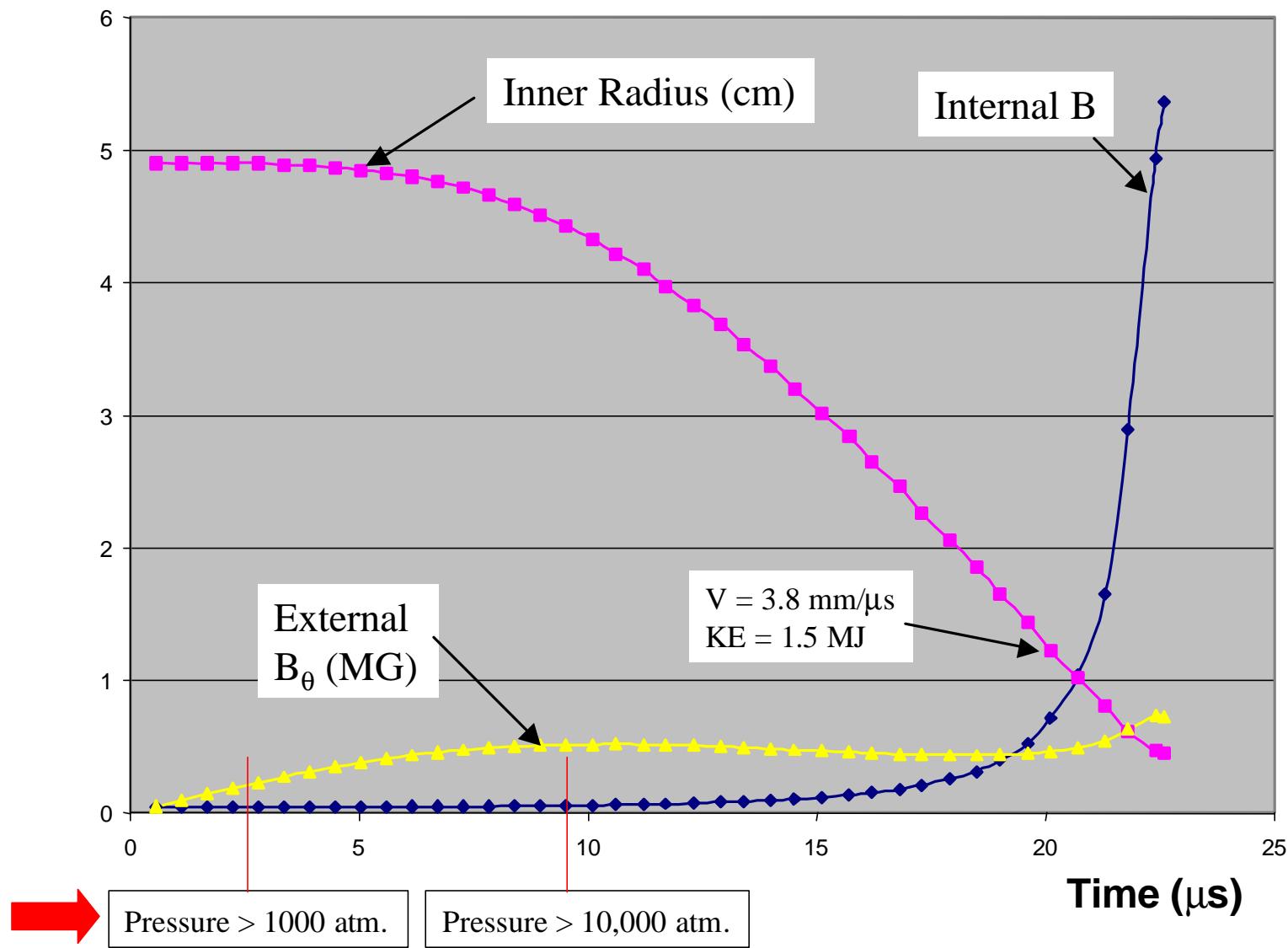
Impact of liner creates shock; heated fiber emits infrared.
Fast-rising signal with no precursor indicates solid metal impact.

On-axis fiber optic and B-dot array

10-mm-diameter G-10 fiberglass tube suspended from top

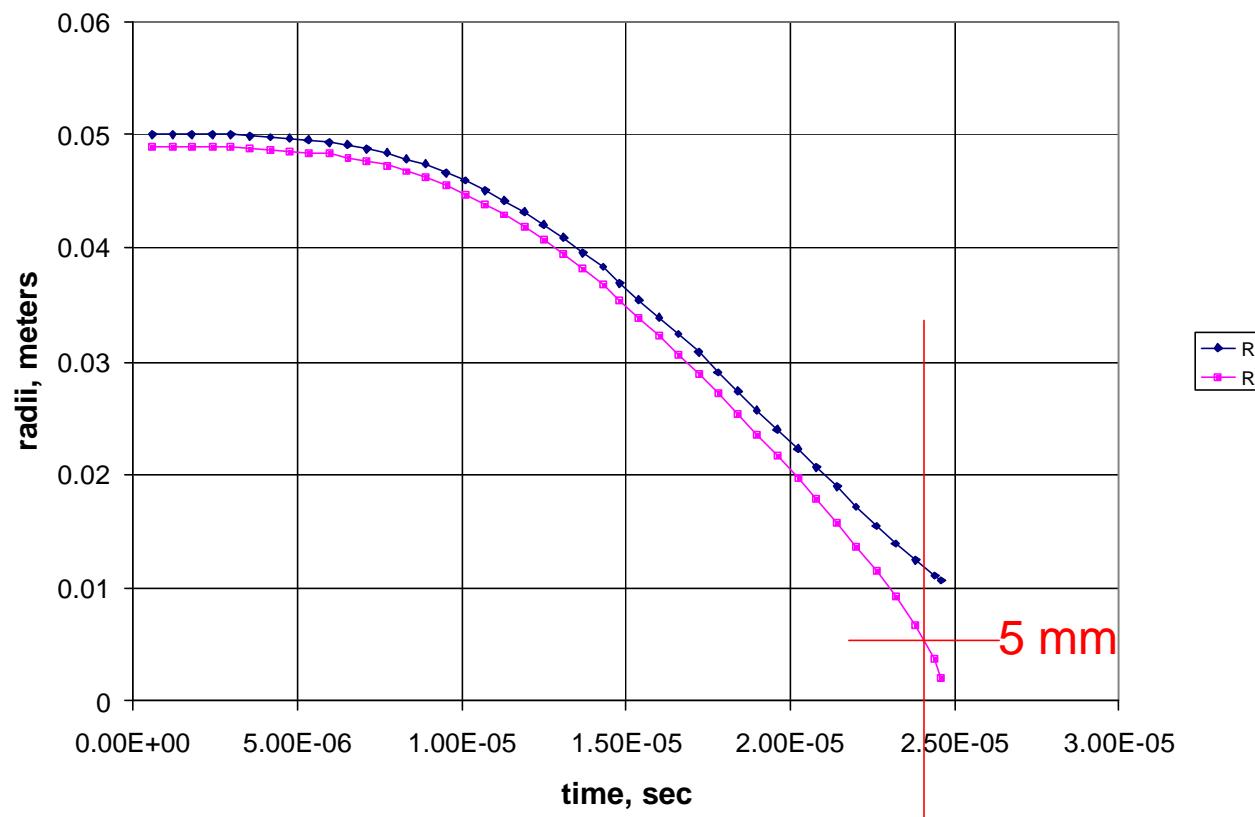


Predicted Shiva-Star liner implosion

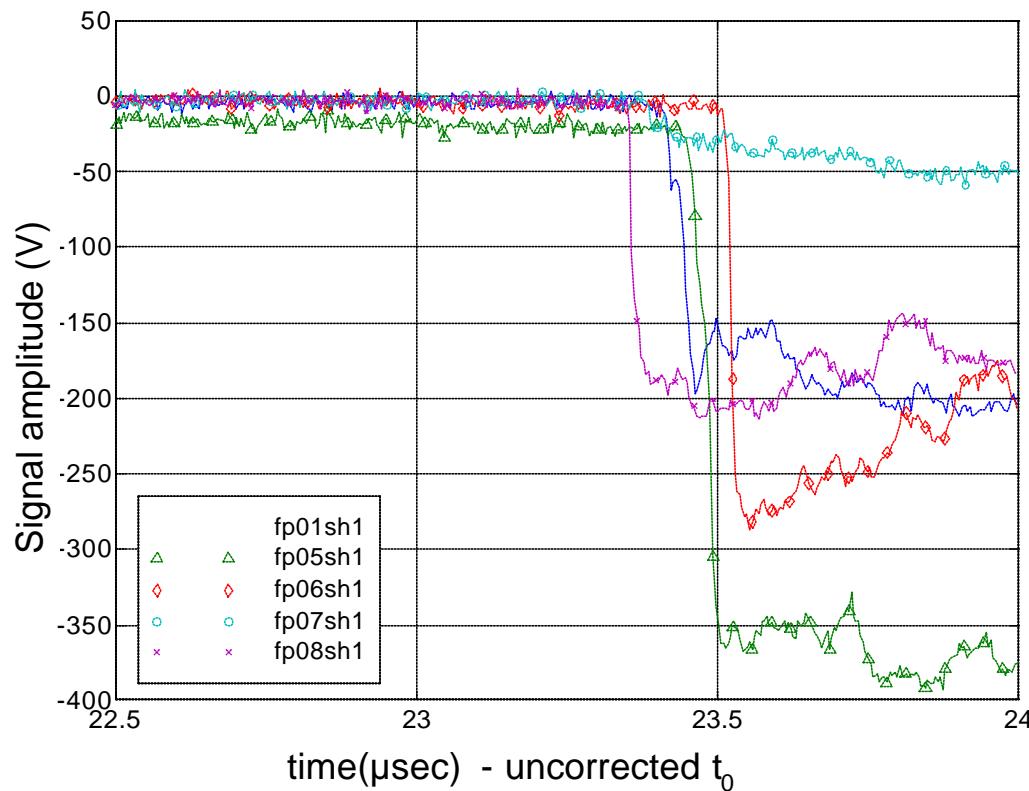


Calculated outer and inner radius vs. time (incompressible liner model)

radii vs time, $C = 1.3$ millifarads, $L = 44$ nH, $R = 1.0$ milliohm + safety fuse, $V_0 = 80$ KV, $h = 30$ cm, $r_o = 5.0$ cm, $dr = 0.11$ cm, $B_z \sim 0$

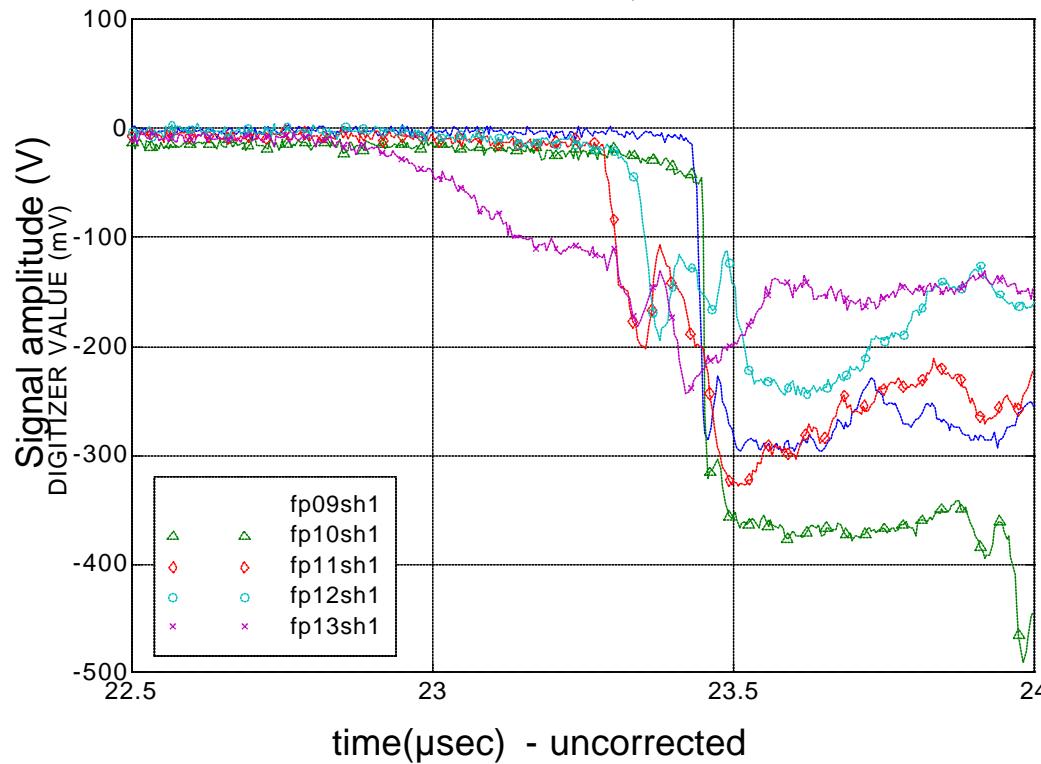


Fiber optic signals – near mid plane



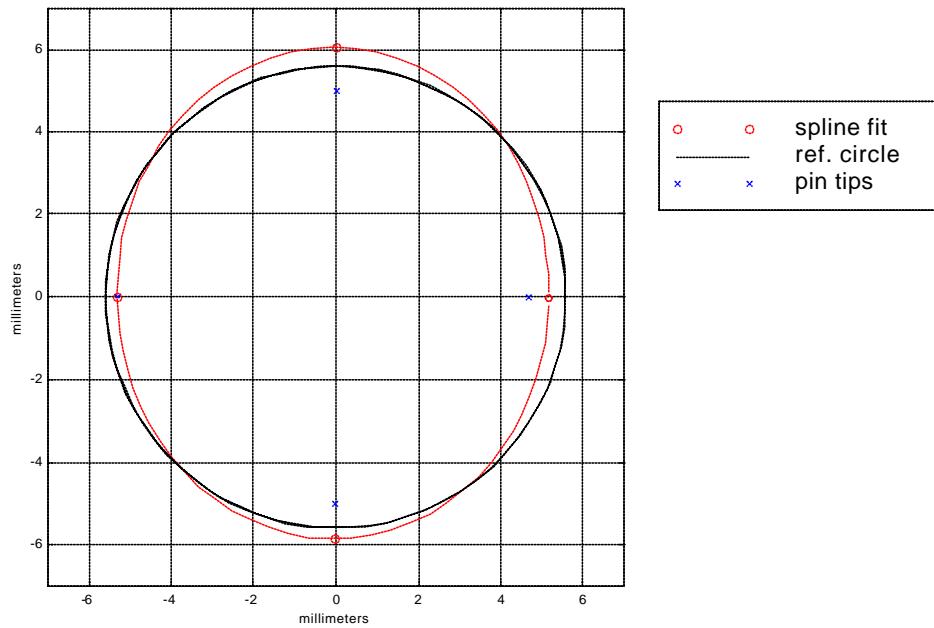
- mid plane detectors show abrupt signal rise, unambiguous impact arrival time

Fiber-optic signals near glide plane



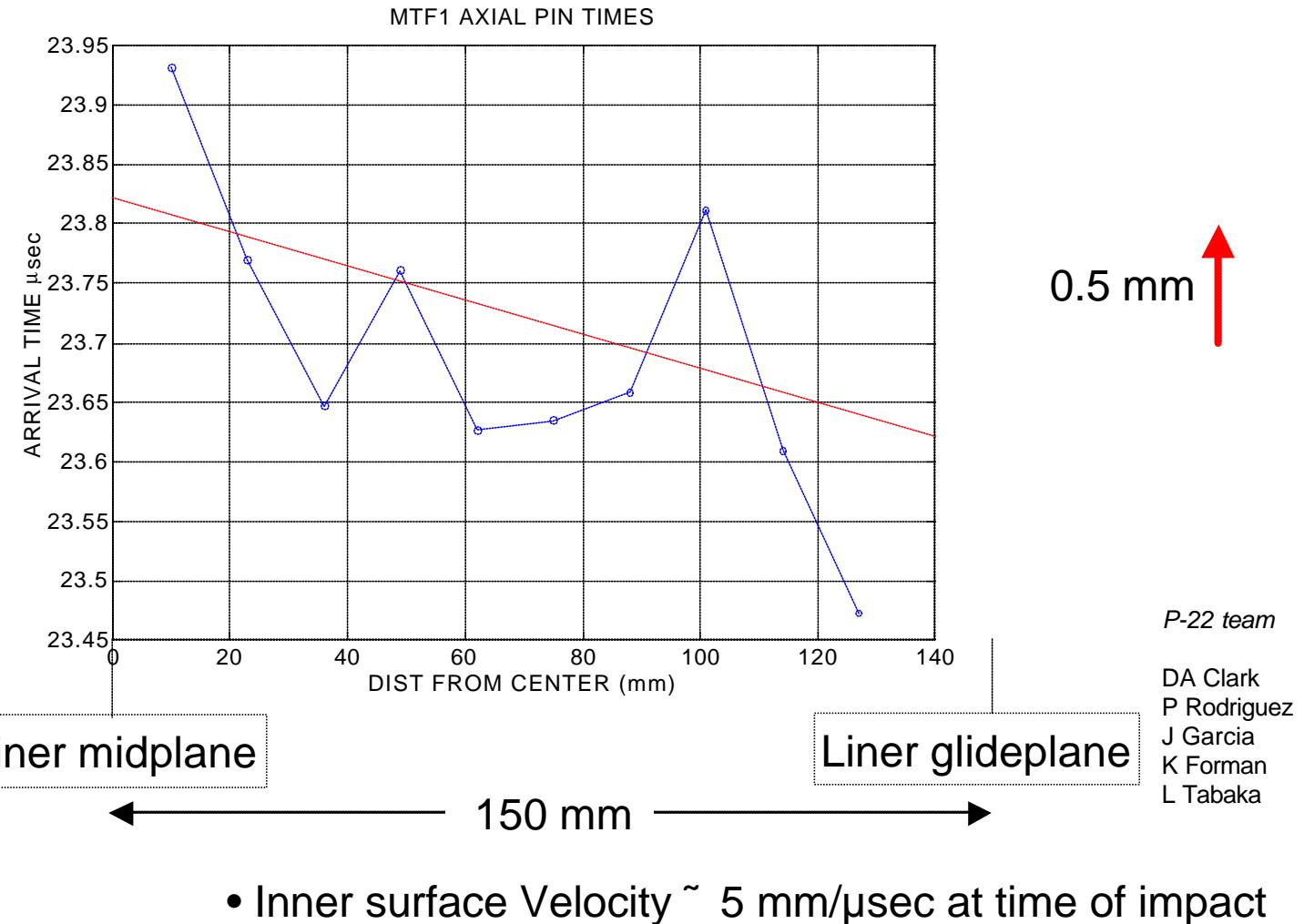
- fp13 [fiber near top glide plane] shows gradual rise in signal
 - ~ Possibly arcing and sparking of plasma near glide plane gradually eroding foil covering fiber
- All other data show abrupt signal rise, and unambiguous impact arrival time

Midplane liner shape at time of impact on optical probes



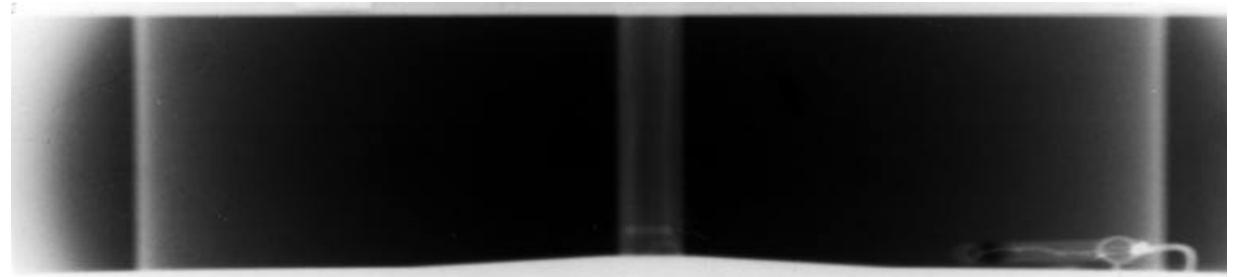
- ☒ Data from four azimuthal pins located 10mm above midplane
 - ☒ Locations of pin tips are shown as blue ‘x’.
 - ☒ The red line is a spline fit to the data points
- ☒ distance = arrival time \times 6mm/ μ sec velocity.
- ☒ black circle = perfectly circular, average of the red points

Fibers shows small arrival time variation middle to end

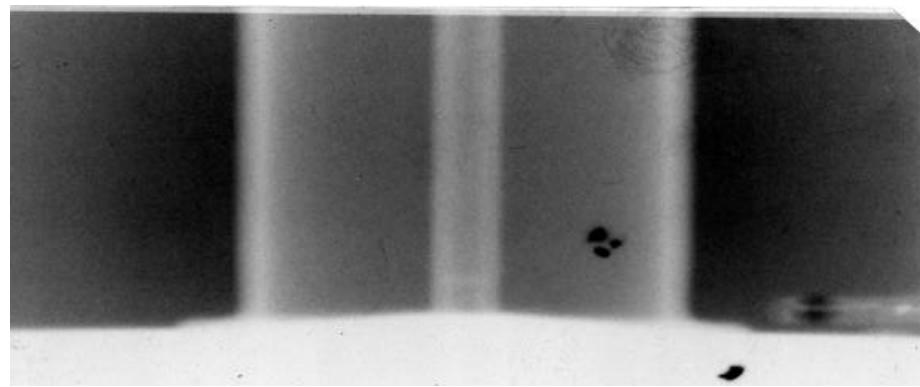


Lower-glide-plane radiographs

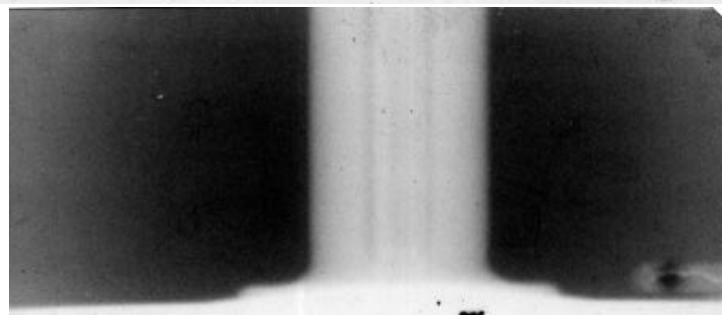
Radiographs $t = 0 \mu\text{s}$



$t = 20.0 \mu\text{s}$

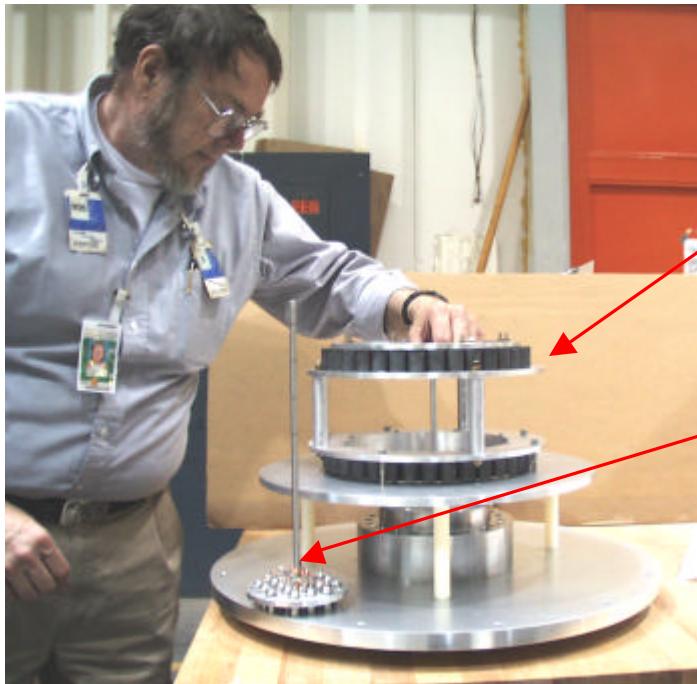


$t = 23.5 \mu\text{s}$



- *Stationary 6.4-mm stainless tube is visible in the center*
- *Thickness of incompressible liner at 23.5 μs should be 7.7 mm*

Seed magnetic field from permanent magnets



- Liner (not shown)
- Permanent magnets
- Faraday crystal inside
- Bdot probe
- Fiber optic impact probes not shown

Bdot probe array

$5 B_z$
 $5 B_r$
Wound &
counterwound Bdots
are overlaid for CMRR
20 channels total

Midplane 0.0 cm

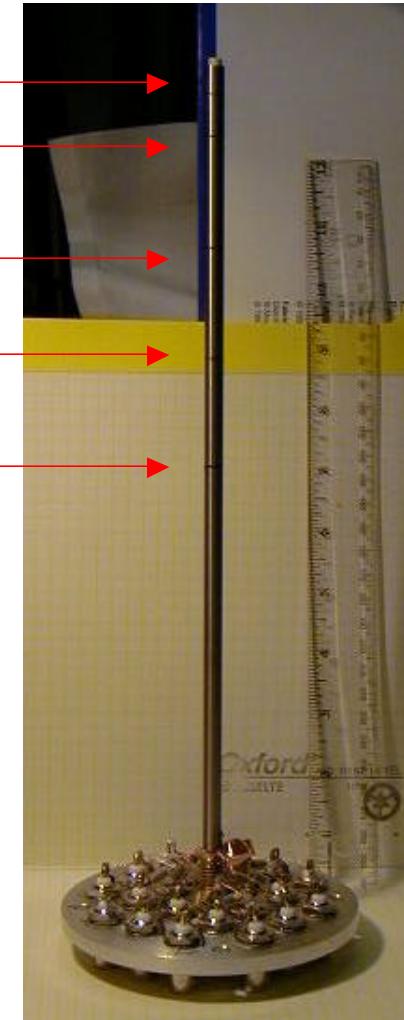
-0.5 cm

-2.1 cm

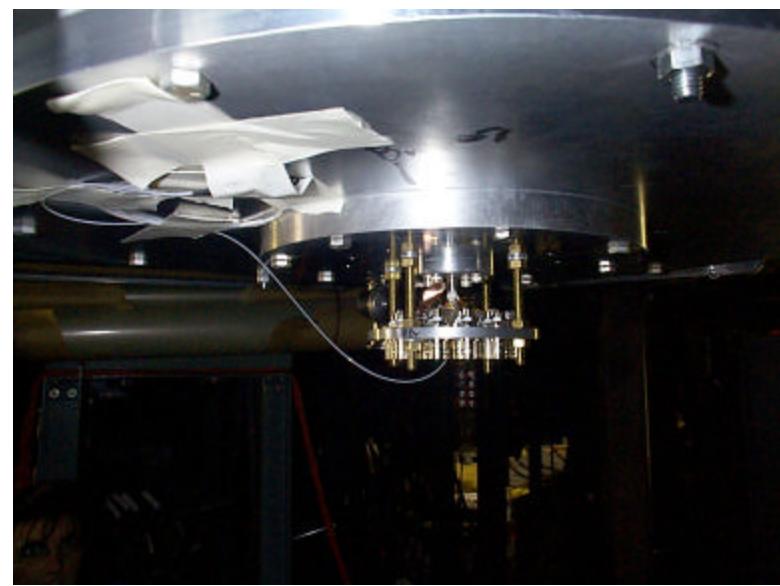
-6.1 cm

-10.2 cm

-14.2 cm



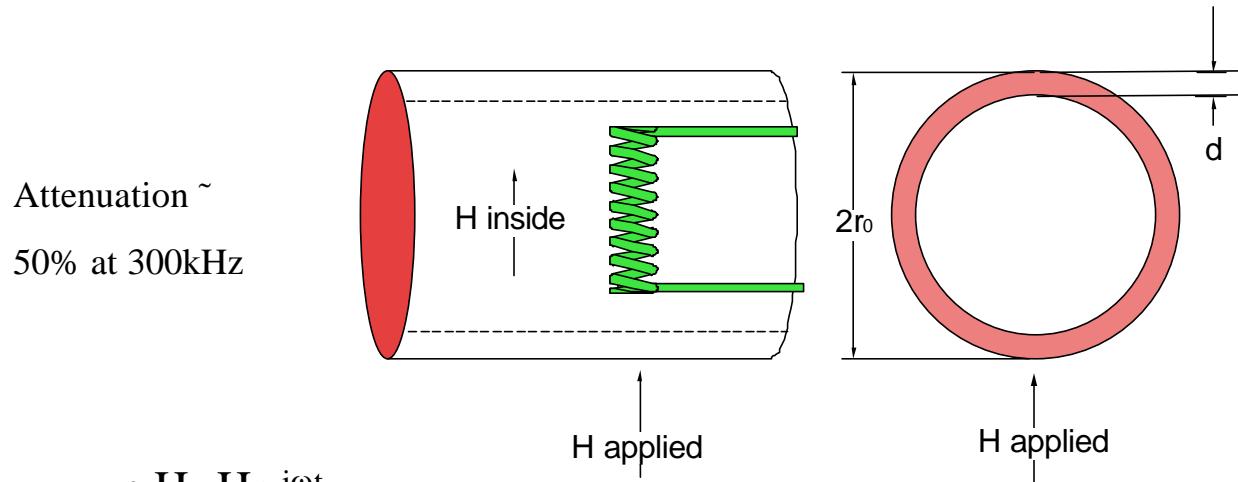
Carefully slide the Bdot package up into the liner, seal with O-ring, bolt it up



Faraday fiber threads the axis

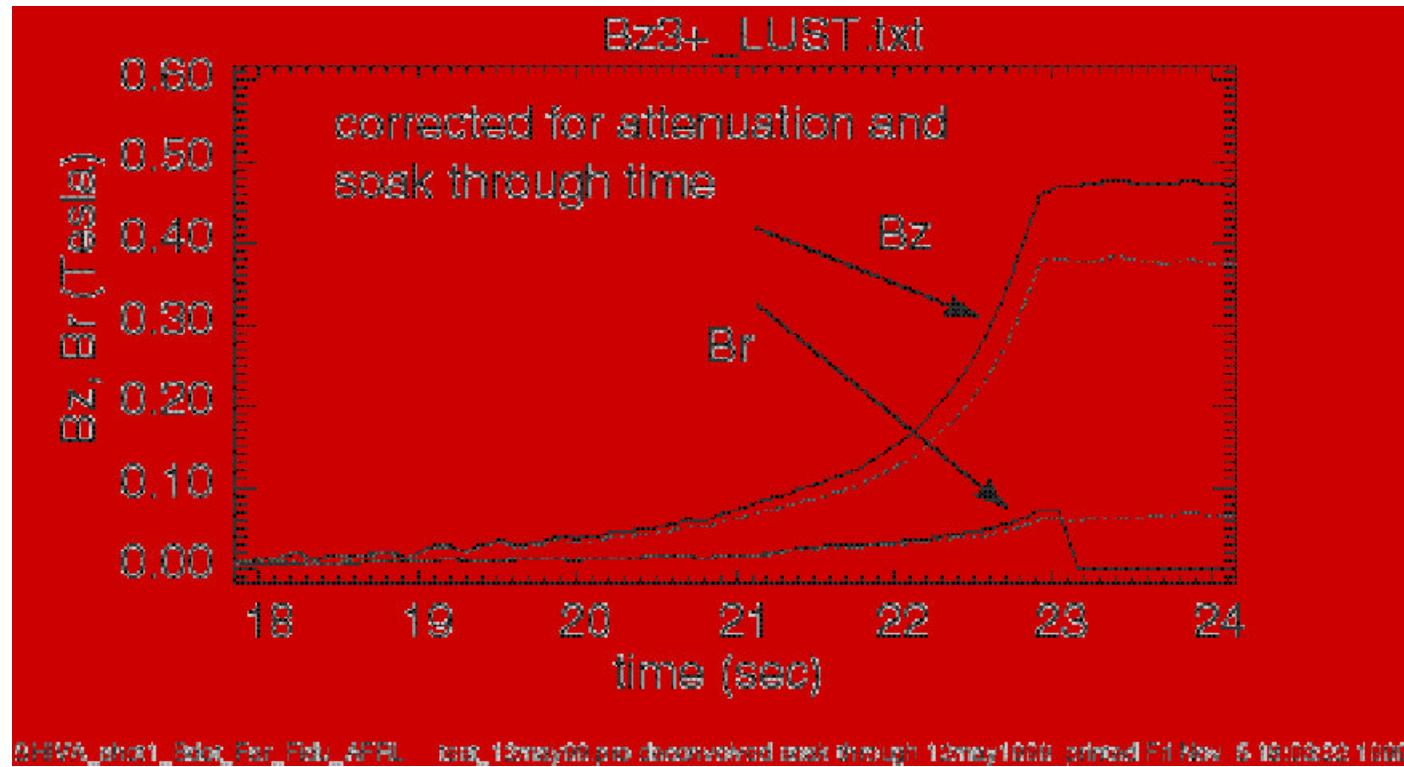
SS tube around Bdot probe adds attenuation and time delay as magnetic field soaks through cylindrical wall

- Deconvolve response with FFT of data, IFT back to time domain
- Skin depth of homogeneous tube surrounding Bdot coil
- $\eta=1/\sigma$ =resistivity, $\mu=\mu_0$, r_0 =tube radius=3.2mm, $d=0.25\text{mm} \ll r_0$

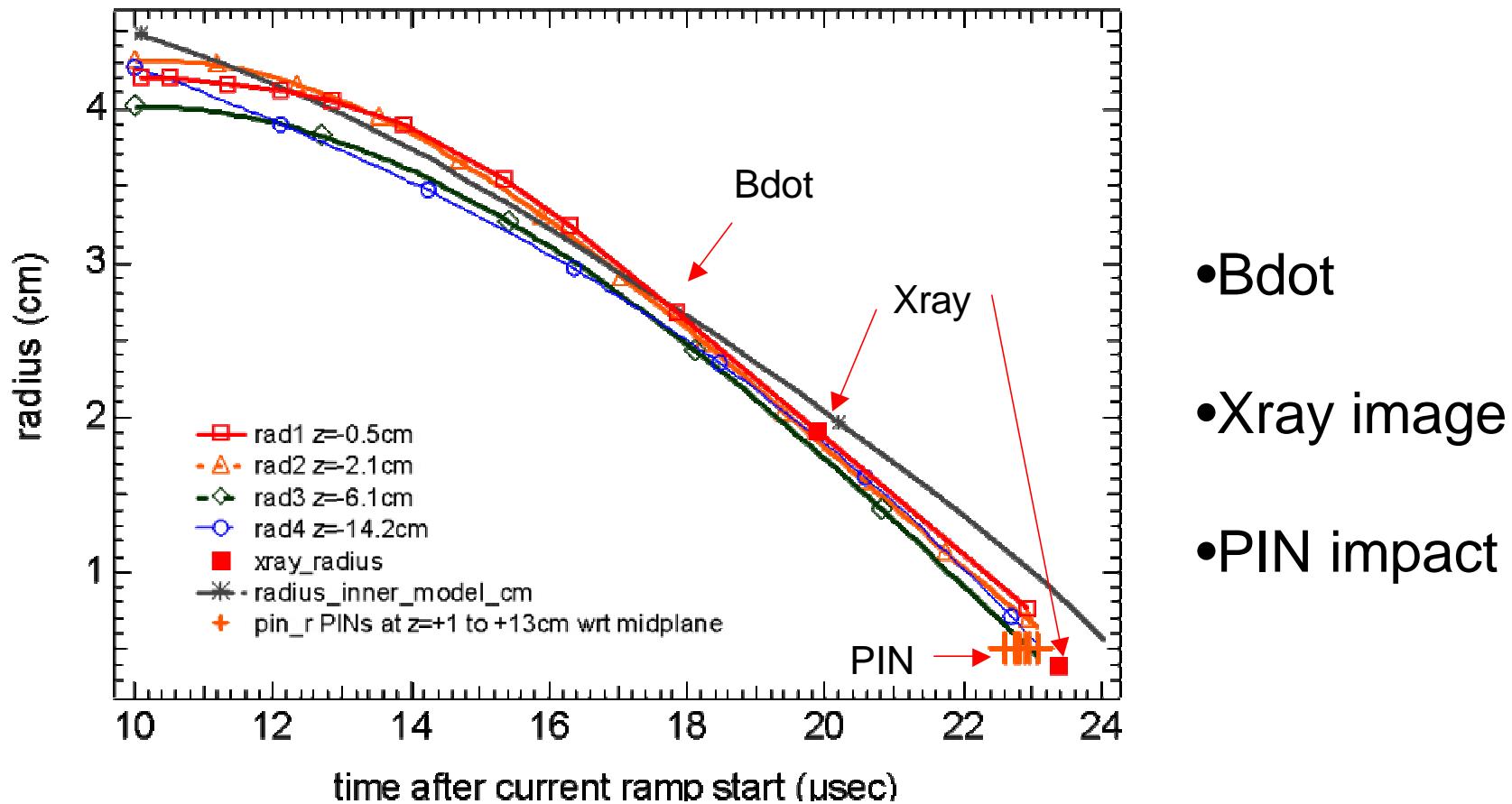


- $H=He^{-i\omega t}$
- $H_{\text{outside}}/H_{\text{internal}} = \cosh(kd) + 1/2r_0k[1 + 1/(kr_0)^2 \sinh(kd)]$
- $k = 1/d$
 $= (1+j)(\mu_0\omega\sigma)^{1/2} = \text{inverse skin depth}$

Typical data has Bz & significant Br



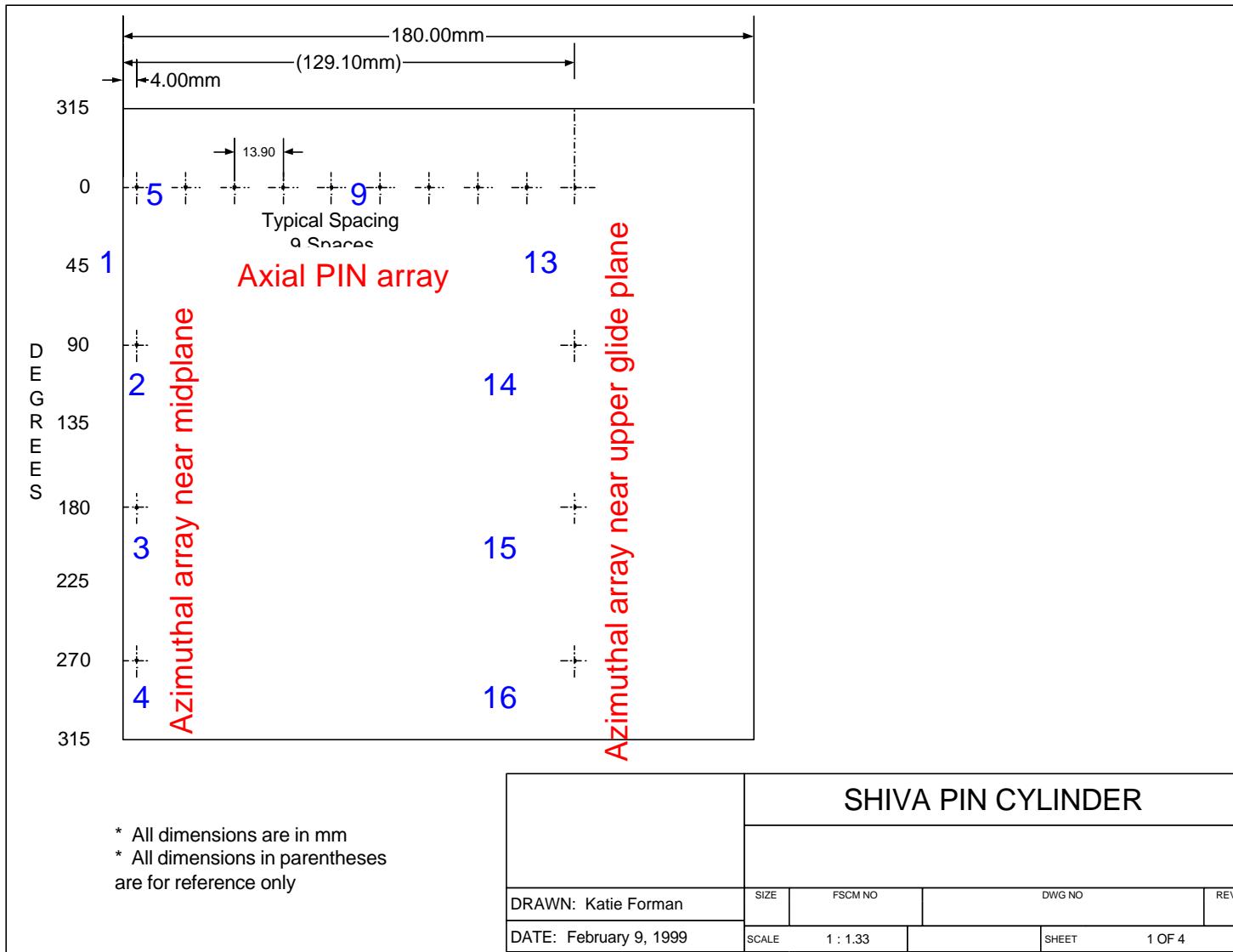
All radius vs time data agree



Summary

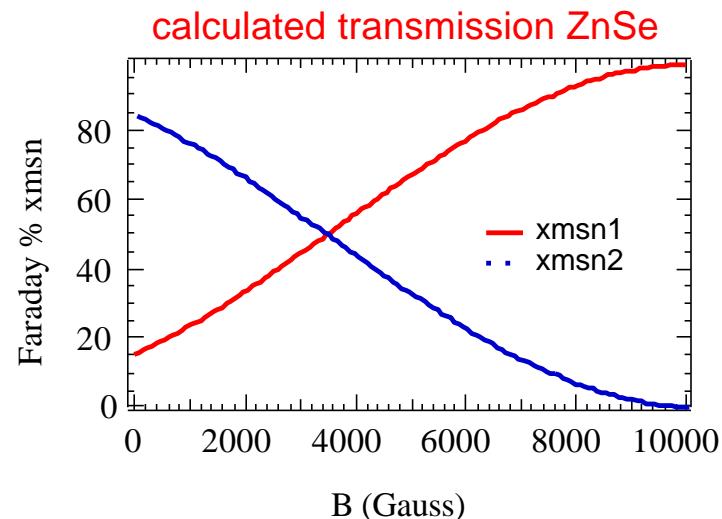
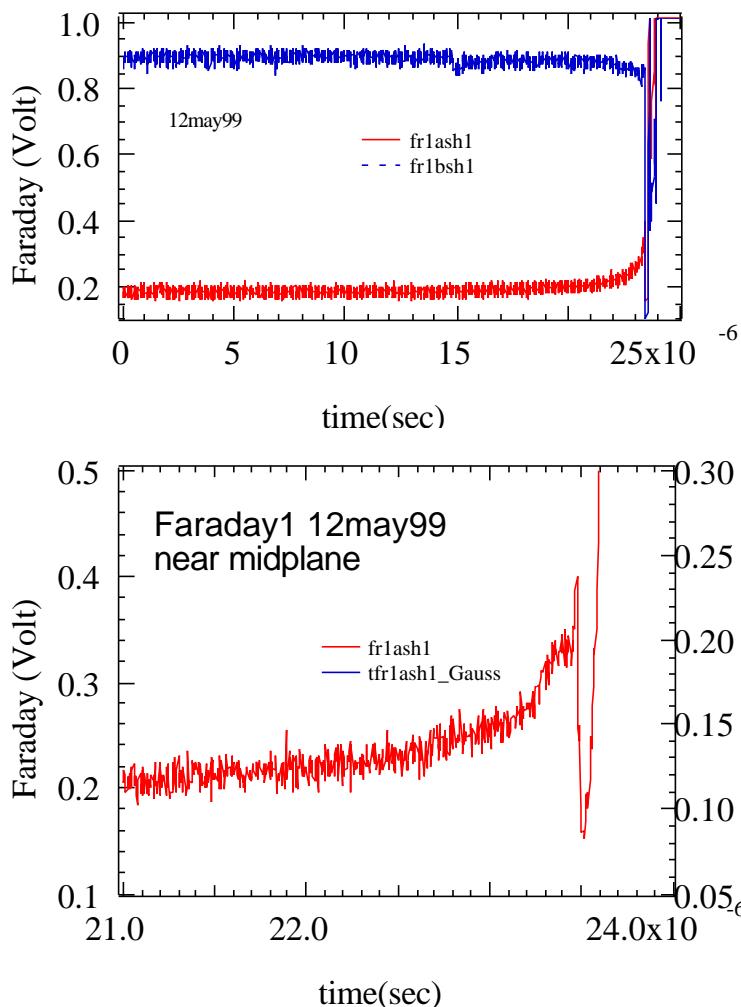
- SHIVA liner experiments were successful
 - Liner technology works as expected
 - Cylindrical symmetry is excellent
 - Multi institutional collaboration of AFRL, LANL
 - Array of diagnostics is consistent – Impact fiber probes, radiographs, B_{dot} , Faraday
- In FY2000 plan to finish design and construction of MTF target plasma formation experiment

Following slides in reserve



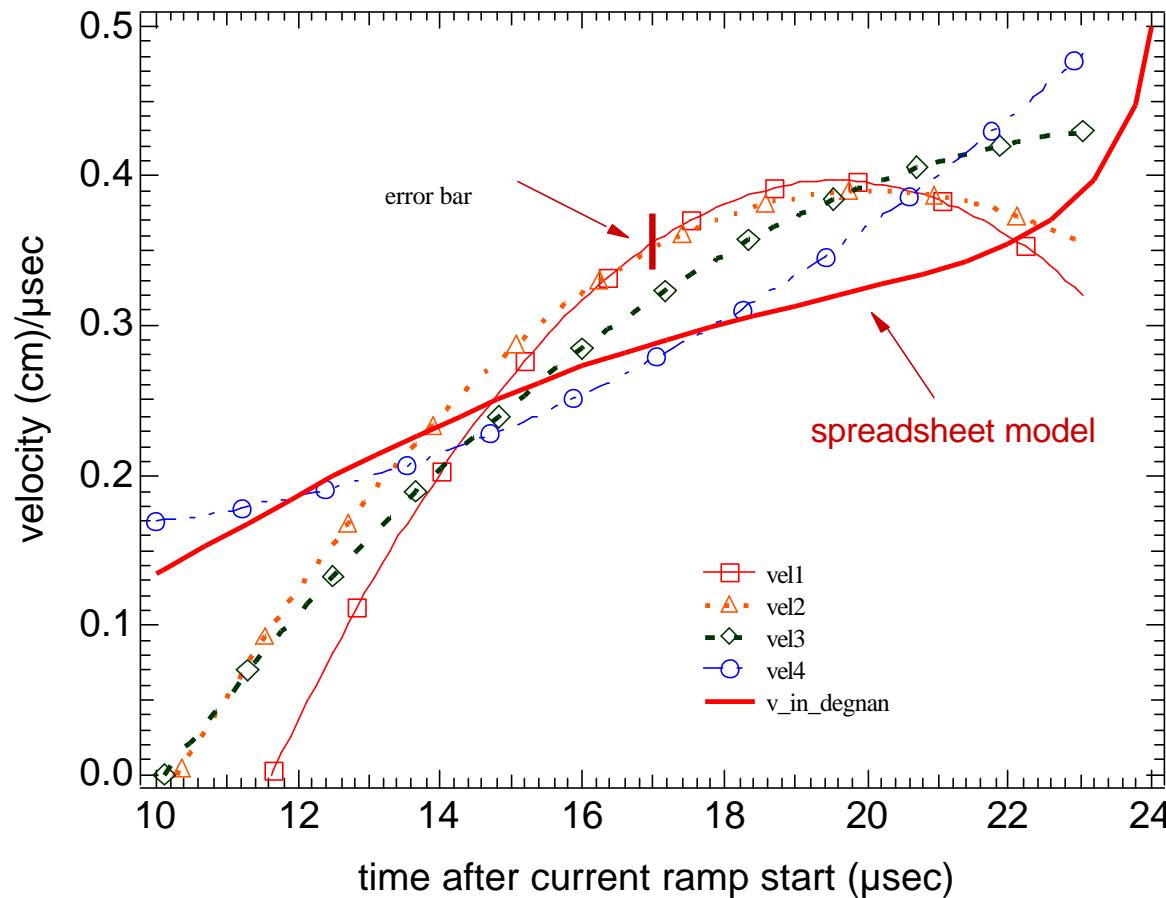
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Novel ZnSe Faraday crystal diagnostic is sensitive to low magnetic fields



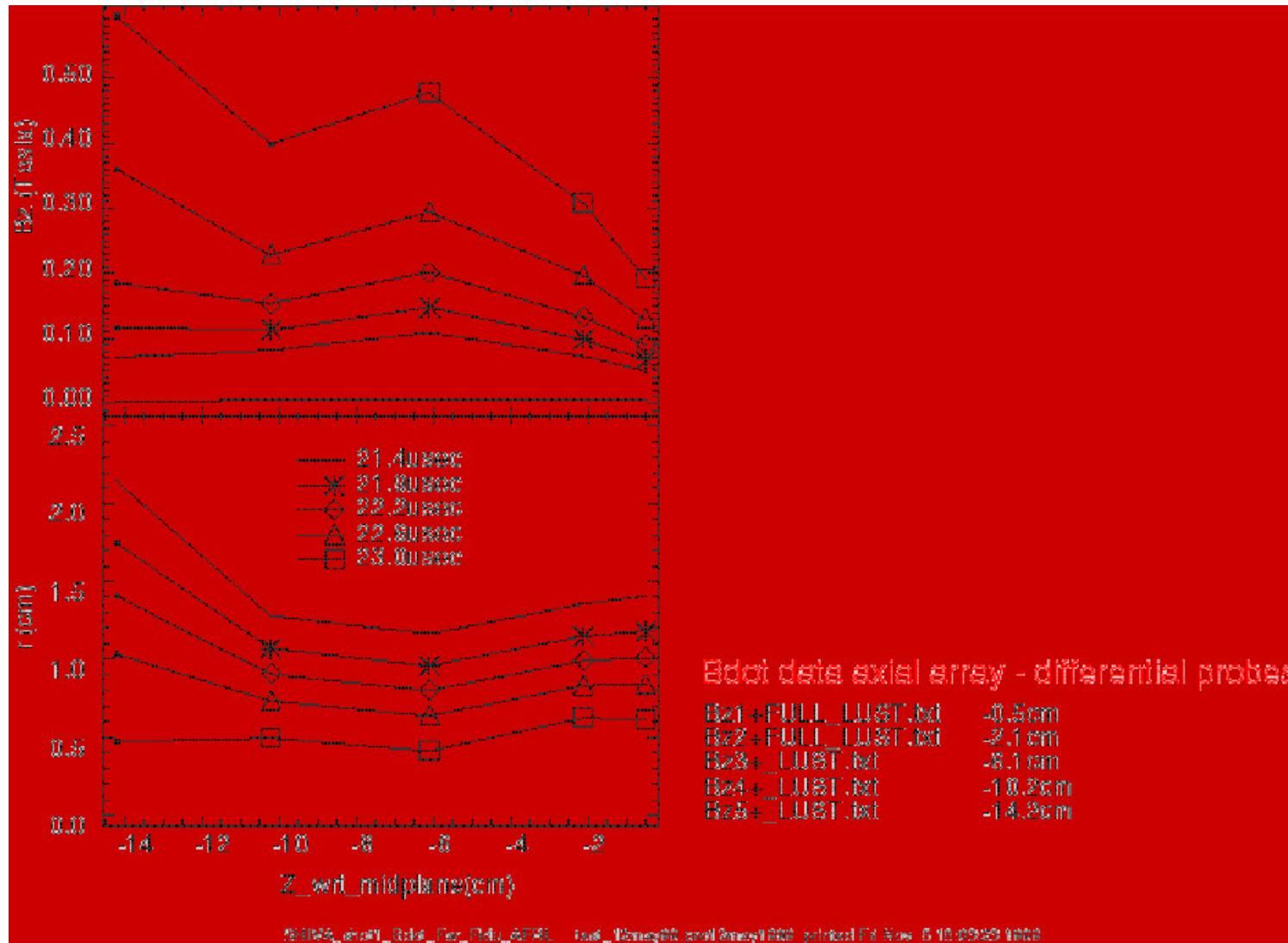
SHIVA shot 1
12 May 1999

velocity vs time at several axial locations



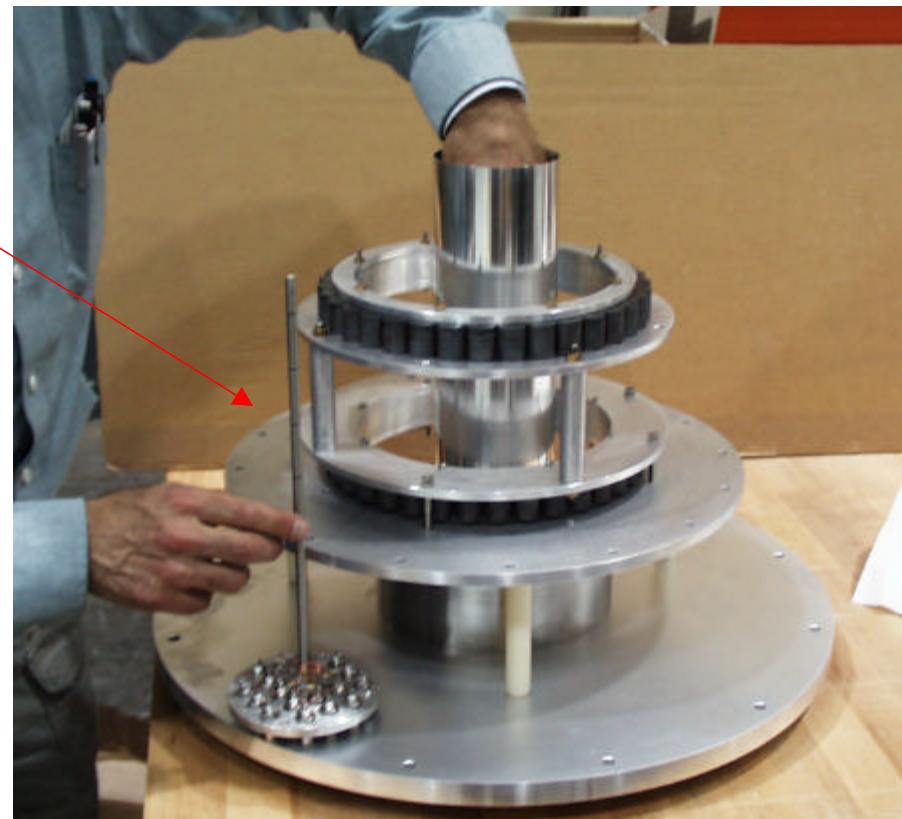
- Bdot data
- Velocity derivatives have larger error bars than radius data

Shape of liner inferred from Bdot array data

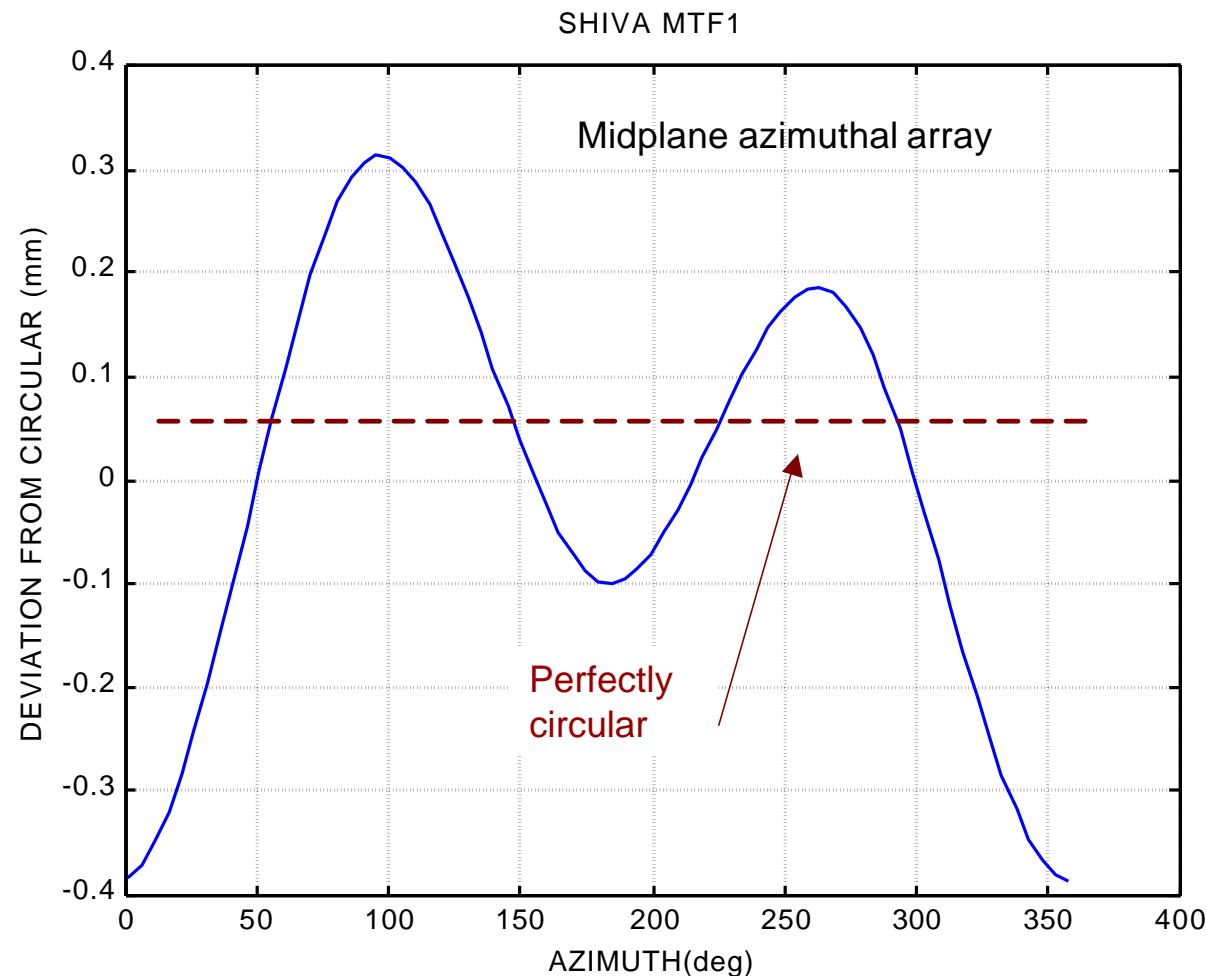


Bdot axial probe array inside 1/4" SS tube

- 5 B_z + 5 B_r Bdots are overlaid, wound + counterwound for CMRR
- Faraday crystal inside, mode locked fiber threads the axis
- Fiber optic time of impact probes (not shown)

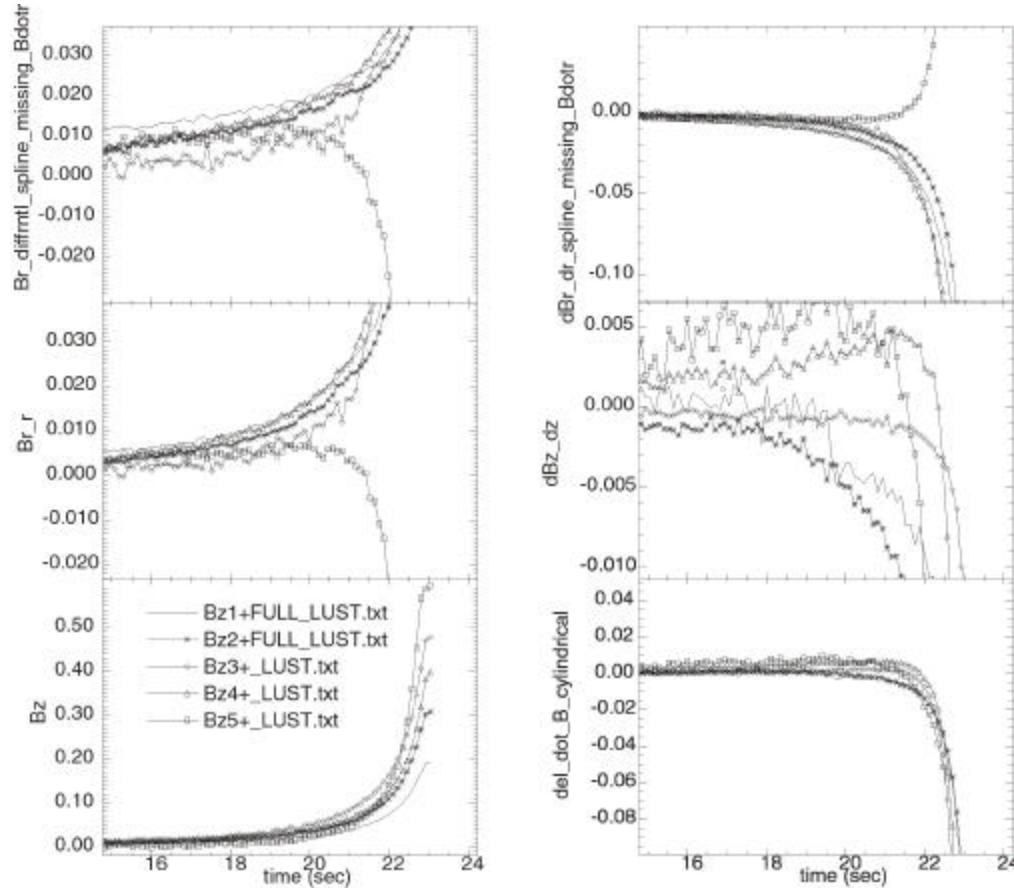


Deviation of spline fit from reference circle



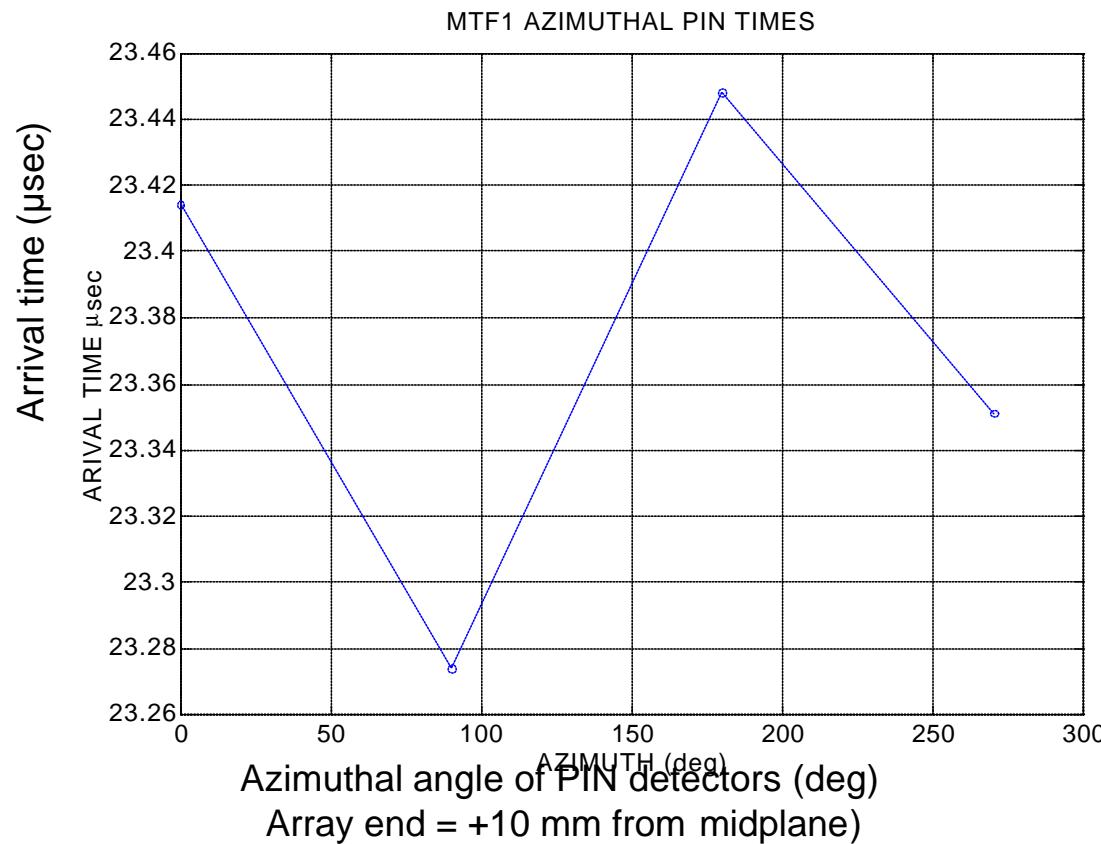
Azimuthal angle of PIN detectors in midplane azimuthal array

Large Br and Bz with cancelling derivatives



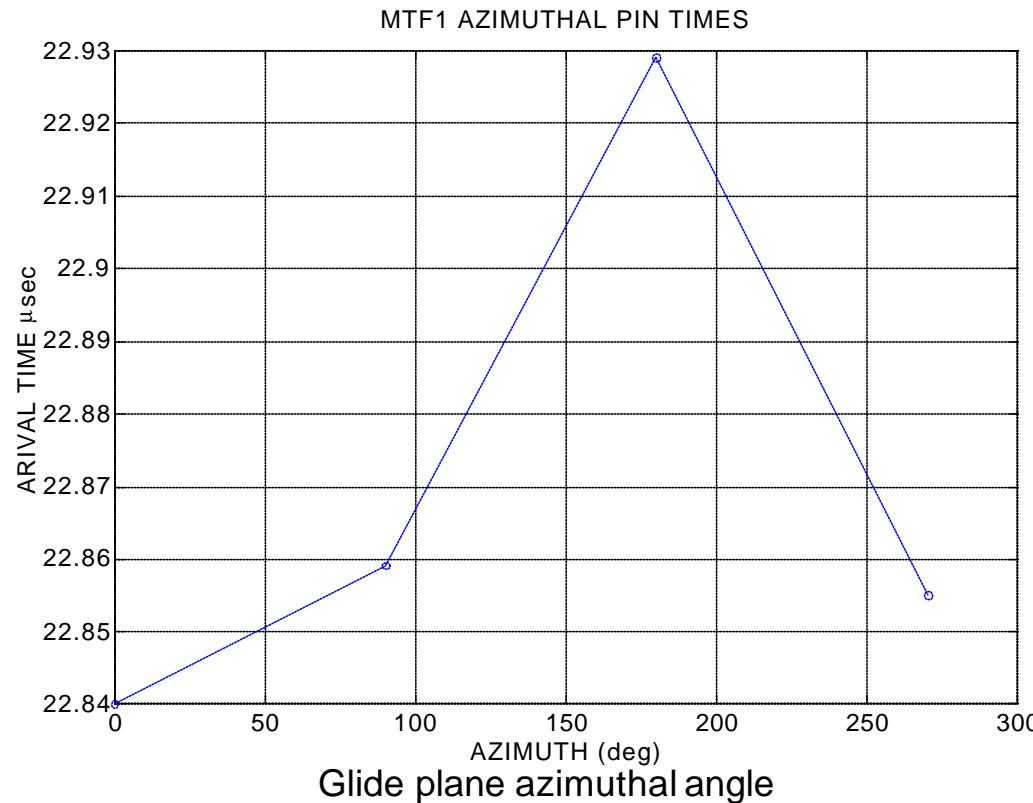
$$\nabla \cdot \mathbf{B} = Br/r + dBr/dr + dBz/dz$$

Azimuthal arrival times near midplane



P-22 team
DA Clark
P Rodriguez
J Garcia
K Forman
L Tabaka

Azimuthal arrival times near glide plane



P-22 team

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P Rodriguez
J Garcia
K Forman
L Tabaka

PIN array detects arrival time of shock from imploding cylindrical liner

- Axial array of 10 PINs distributed from midplane up to top glide plane
- 2 Azimuthal arrays 4 PINs each at glide plane & midplane
- Time resolution \sim 50 nsec

P-22 team

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